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Management of personal safety risk for lever operation in mechanical railway signal boxes

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A B S T R A C T

Despite increased implementation of computer control systems in managing and regulating rail networks, mechanical signal boxes using lever operation will be in place for years to come. A rolling risk assessment programme identified a number of levers in mechanical signal boxes within the UK rail network which potentially presented unacceptable personal safety risk to signallers. These levers operate both points and signals and the risk is primarily the weights which have to be moved when pulling and pushing the levers. Operating difficulties are often compounded by the design and condition of lever frames, the linkages to the points/signals, maintenance regimes, the workspace and the postures and strategies adopted by signallers. Lever weights were measured as from 15 kg to 180 kg at over 160 boxes, using a specially designed and constructed device. Taken together with examination of injury and sickness absence data, interviews and field observations, and biomechanical computer modelling, the measurement programme confirmed the potential risks. A risk management programme has been implemented, comprising lever weight measurement, training of operations staff, a structured maintenance regime and renewal or redesign for boxes/levers where, after maintenance, a criterion weight level is still exceeded. For a feasible management programme, the first alert (or 1st action) value for further assessment is 55 kg, a second action level requiring specified maintenance is 80–99 kg, and a third action level requiring the lever to be signed out of use is 100 kg.

1. Introduction

For industries in complex and often safety critical environments the human factors contribution to safety is increasingly at the socio-technical systems and safety management level. It is perhaps easy to assume that all or most physical ergonomics concerns are by now fully understood in such systems and industries. Their physical health and safety potential problems may not have been entirely designed or managed out but we possibly assume that at least all the research needed to address problems of manual handling (in all its senses) has been completed.

This paper concerns just such a particular physical health and safety problem which emerged whilst a rail infrastructure company was largely concerned with human error and organisational failure at a systems and safety management level. Indeed from the earliest research in rail human factors through to the current day there has been very much a concentration upon socio-cognitive issues such as train driver vigilance and attention and signals passed at danger, and signaller/controller expert strategies and mental workload (see Wilson et al., 2005, 2007, 2012). The physical health and safety problem covered in this paper exists due to the continuing use, for good operational reasons, of legacy signalling technology alongside much newer and more sophisticated operating systems. In the UK and other countries, rail network control is moving into larger, computer-based and centralised control centres and using advanced train control and traffic management systems. However, for now the signal boxes in the UK are a mix of NX (entry–exit) control panels and VDU-based systems, but also with many mechanical lever operations. Levers are used in more than 500 of Network Rail's signal boxes and centres, with between 8 and 200 levers in each. Levers are used for two main operations – setting signals and changing points.

The first author (BM), an operations expert with ergonomics training, had been called to a mechanical signal box as part of a rolling programme of assessment of mental workload, irregular working and human error. What became apparent, through

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observation and subsequent discussion, was that signallers in that box were struggling physically to operate the levers. Over the next three years, in large part because of the investigations reported here, increasing numbers of reports of difficulty, discomfort and injury, claimed as the consequences of working with levers, were identified across the UK network. Difficulty in operating rail signal box levers is not a new phenomenon as seen from a report of early last century (and see Fig. 1):

> "Mrs Kathleen Willingham, 36 years old and married with children, worked from 9 a.m. until 10.30 p.m., a 91-hour week, at a level crossing near Colchester. She had to pull a very heavy lever 144 times a day. The LNER provided a stand-in for only seven hours a week 'shopping leave'. Her application for a pay rise to compensate for taking over her husband's duties was declined. She asked to get her hours reduced but the LNER treated her as a part-time employee because she could 'run home between trains'. They argued further that she knew the duties of the job when she accepted employment. Men were allowed to work only eight-hour shifts." (Fig. 1).

(Excerpt from article on a web site called Signal Box. (Quote and picture in Fig. 1 appear with permission of Wojtczak (2005)).

This paper reports research initiated by the Network Rail Ergonomics Team to understand the level of physical injury risk from operating in lever frame signal boxes. This was a study to decide on whether there is a problem, the extent of it, and to set a management strategy to go forward in mitigating any risks in future. Initial observations generated research questions, the most important of these being: What is the safest method of pulling levers? What are safe limits to the weight to be operated? And what methods could be used to limit and manage any risks? The lever frame technology is particular to the railway, has been in place for a long time, and is therefore not compliant to modern standards. Moreover, there was nothing in the established literature to help in answering the questions. A project was set up to include observation and analysis of methods of lever operation, measurement of the weights being moved, and recording of environmental and other influences on the methods of operation. Data collected were to support recommendations for a programme of maintenance and modifications to those levers and frames where risk is assessed as the greatest, and of training in improved pulling techniques. It is recognised however that without a substantial longitudinal study it might be difficult to categorically attribute any signaller's injury to their work, as activities outside the workplace may have triggered or contributed to the physical problem.

The paper first of all explains the background to rail signal box lever operations, reports any related literature and attempts to interpret some relevant guidance from this. Then the methods of the study are described, consisting of field observation, direct measurement, interviews and self-rating, analysis of injury and lost work time statistics, and some limited computer biomechanical modelling work. Details are then given of the management programme which Network Rail will initiate as a result. The main objective of the research and of this paper is to detail and support the development of the feasible risk management programme rather than focus on the more narrow issues of lever weights and consequent forces in the human body. It is emphasised that the risks referred to are ones of personal safety through the actions of pushing and pulling levers. Although the railway has many areas of systems safety concern, this is not one of them since the secondary safety back-up will prevent safety problems from train routing even in the event of sudden signaller injury.

2. Background

2.1. Types and operation of signal box levers

Although rail signal box levers and frames all work on the same basic principles, there are a large number of different frame and lever designs. This has come about due to them being often designed and built local to the area where they were installed, many over 100 years ago. The levers are used within the mechanical form of signalling which was developed during the 19th century to control the movement of trains. Although dated, lever frame signalling is likely to be with us for a good while longer yet. Mechanical signal boxes (e.g. Fig. 2) have their connection to external devices – such as signals and points – by wire and channel rodding attached to the levers within a metal frame. There are many variants of frame and lever types, along with different release types (triggers and stirrups). The connectivity between lever and the object to be moved gives some clue as to the differences in lever pull weights.

Fig. 1. Operation of a very early rail lever.

Fig. 2. Typical mechanical rail signal box.

For signals, the standard design is a wire connection from the tail end of the lever through a system of pulleys and detectors to a counter balanced weight fitted to the bottom of the signal post (Fig. 3a). Signal operation through the wire pull has inbuilt slack and elasticity in order to facilitate temperature changes. This therefore allows the signaller to 'take up' the slack in the first part of the lever pull and so giving the opportunity to use the momentum and their body weight to move the object.

For points the design and operation are connected up through a solid rodding system (Fig. 3b). Point operation is through connectivity of solid rodding bars (to maintain gauge allowance for point ends) and so there is no 'slack' in the system when pulling the lever. This means that the full weight is experienced by the signaller from the start and throughout the entire pull.

Whilst the weight to be pulled (and pushed) is the major factor examined in this study there are other potential hazards in the operation of the levers. Being a mechanical system the connections are prone to sudden failure, often unexpected despite inspection routines, and which could result in acute injury. Also, the long runs of the rods or chains through varying terrain means that they are prone to blockage through bank slides and the operator would have no way of knowing this until trying to take up the weight.

2.2. Previous relevant research

The industry assessment of operability of levers with respect to their manageability is currently by reference to the length of the connection, with no consideration given to weight of pull. This does not appear to follow recognised health and safety thinking and guidelines and regulations (such as those for manual handling), but the lever systems have been around since long before current guidance was developed. The rail industry does work to a number of Railway Group (mandatory) Standards, and Network Rail itself has standards and guidance which may go beyond the legal requirements. Relevant guidance states that: "The maximum recommended distance at which signals can be mechanically operated is 1000 yards which minimises the effects of temperature change on wire routes", and elsewhere that "wire operation of mechanical signals should be limited to 1000 m". Thus there is some discrepancy in the various documents which make it difficult to determine which distance is most appropriate to use as a reference. Originally signal boxes tended to be close to points in an attempt to lighten the weight of the pull, but this is not always achieved. Current codes of practice state that "200 yards satisfy the Health and Safety Executive" and "manually worked points should not exceed 320 m rodding run from lever to furthest point end". The requirements are in the company's own code of practice, to which signalling engineers generally work, but may be challenging and restrictive to achieve from an engineering point of view.

The question that arises is; what is a safe lever weight or effort that an operator can exert given the nature of the task? There is literature on lever pulling but not for full length levers; Page et al. (1990) and Attebrant et al. (1997) examined loads working with hand levers. The former was at railway point switches, but due to the much smaller size of levers this US work concentrated upon hand forces not on whole body movement, and there are no lever frames nor other levers in close proximity to inhibit access; their measured actions also start with the lever parallel to the ground with a lifting movement from a static position and no connectivity through wires or rodding. In a more general description, Kroemer et al. (2001) suggest that large levers used occasionally should have an operational force requirement of less than 190 N. They also find that improved pulling force is achieved with one foot off the ground. Resnick and Chaffin (1995) found peak push forces of 500 N for men and 200 N for woman in pushing of carts of between 45 and 450 kg, and found consistent results for static compression forces at L5/S1 above the NIOSH action limit of 3400 N with stronger participants and loads of above 225 kg.

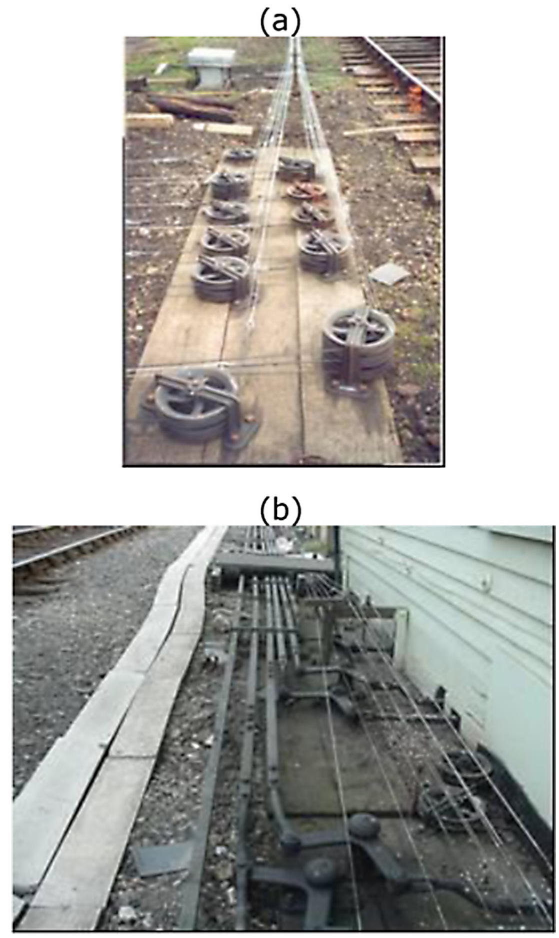

Fig. 3. Connections from levers to (a) signals with a wire running through a system of pulleys and a counter balance weight at the signal; and (b) points, with solid rodding running from the tail end of the lever through a system of cranks.

Nothing more specific was found in the literature and so the general ergonomics guidance on pulling/pushing was examined. Much of the manual handling literature is concerned with lifting and related manual handling tasks. The maximum pulling and pushing forces of the hand during standing work have long been studied, for example by Rohmert (1966) and Rohmert and Jenik (1971) (both quoted in Kroemer and Grandjean, 2000). Pulling forces are greatest in the vertical plane and lowest in the horizontal plane. Pulling and pushing forces are of the same magnitude whether the arms are held out sideways or forwards (in the sagittal plane). Maximum pulling force depends on height and distance of the pulled element, and body weight and posture are of critical importance especially the stance for pulling (Ayoub and McDaniel, 1974). The same authors generate design guidelines around limits on pull height and distance – a maximum pulling force for men of between 40 lb and 150 lb, and for women of between 50 lb and 90 lb, depending on height and distance. They also find that improved pulling force is achieved with one foot off the ground.

Review papers covering a wide range of contributions to do with pull/push forces include Gallagher and Heberger (2012) and Hoozemans et al. (1998), but these do not cover material to do with pulling or pushing large levers These papers identify risk factors of weight, distance, foot stance, one-handed or two-handed operation, force at the hand, symmetry of pull/push and static or dynamic force application, illumination and temperature, all relevant to an extent to our lever work. They do say that the risks from pulling are harder to predict than those from pushing, interesting given our greater concern with pulling (see below). The amount of force a user can exert on a control depends on posture, position, and the length of time the force is applied. 'Jerk' forces used to loosen tight controls may be two or three times larger than the corresponding maximum steady forces; forces which must be applied over a long period should, it has been suggested, not exceed 15% of the corresponding maximum force over 5 s, although some continuous application may last for much longer without rest (Galer, 1989).

In a variety of other studies risk factors have been identified – none for full length levers and mostly for cart or other moveable object pulling/pushing or else from biomechanical modelling work (for example Boyer et al., 2013; Lin et al., 2012; Seo et al., 2010). The restricted space found in some signal boxes is likely to have some effects – for instance Lee (2007) showed that restricting their space in front of the task reduced pushing strength by about 25%.

Cart pushing and pulling is perhaps one of the tasks closest to lever operation in terms of the techniques used. Lee et al. (1991) showed that pulling forces (98, 196 and 294 N) resulted in the greatest loading, with findings depending on body weight, and that a pulling height of 1520 cm was better for force application than 660 or 1090 cm. In other work, peak pushing forces of 200 N for women and 500 N for men were reached when pushing carts of between 45 kg and 450 kg with consistent compression forces about 3400 N for the strongest participants at weights of over 225 kg.

The government guidelines and regulations of a number of countries were reviewed (eg the Health and Safety Executive in the UK, the National Institute of Occupational Safety and Health (in the USA) and the Work Safe Commission in Australia. A range of limits and guidelines are available, according to the task and other work factors, for instance in the UK the guideline for starting or stopping a load is 20 kg for men and 15 kg for women (Health and Safety Executive, 2004, clause 23). However, there are considerable differences between lever pulling and the lifting and lowering tasks on which guidelines appear to be based and which are used as examples in the documentation. Furthermore, the manual handling literature is mainly concerned with maximum voluntary weights and forces, and the regulations and guidelines generally are relevant to the lifting of free weights. With levers, the operator is pulling or pushing something which is supported by a superstructure and is only free to move in a single plane and in a fixed arc of motion. Finally, the types of additional risk factors concerned with the load – eg being bulky or unwieldy, difficult to grasp, not stable or rigid (HSE, 2004, clauses 131–144) – do not really apply to levers.

Therefore it was considered that any acceptable weight limits for lever pushing and pulling are likely to be different to the existing manual handling guidelines, and are likely to be higher, requiring original work to understand where to place guidance limits for a pragmatic management programme.

Looking beyond the weight of a load, the content of the literature that was certainly relevant to our levers study and to a subsequent management plan, was identification of risk factors such as space to move, the quality of the work environment, presence of any obstructions, sudden changes in weight (due to friction, snagging or jamming in the case of levers, or just overcoming inertia at the start of a pull), and stability and slipperiness of footing.

3. Methods of study

During a two year period more than 160 signal boxes were visited by members of the Network Rail Ergonomics Team for assessment of manual handling risks working with levers. This took place in two phases. First a small in-depth sample was taken where all the levers in each box studied were assessed. Then a much larger pre-screened sample was visited where only levers previously identified as a problem by local staff were assessed. Postures and pulling strategies adopted were noted and the weight for moving the lever(s) measured directly. Other measures taken in many boxes were of risk factors such as lever dimensions, relevant box dimensions (including that of the space in front of the set of levers or lever frame within which the signaller can stand to pull), distance of the pull (ie to the signal or points), and signaller body size and height.

3.1. Direct measurement of weights

The key risk factor for the task, and the priority for investigation, was the weight to be moved by pulling and pushing the lever via sometimes very long systems of wires, rods and channels. Thus a robust, repeatable, portable method was needed to measure these weights in the field. Weight rather than force was selected for measurement because this is the term used within the railway industry – culturally the lever pulls are discussed in terms of their weight – which allowed a clearer understanding of the issues by the signallers and their managers, and by company engineers subsequently. Field study was needed at this time rather than a laboratory study or a computer simulation because the conditions at each box – length of rods or links, condition of the running channels, type of linkages, maintenance history, etc. – would effect the weight to be moved in every case. We also needed to record the postures and pulling strategies adopted in real practice.

As a first pilot exercise a crude prototype measuring device was applied to the levers. This was a strain gauge attached via a looped strap to a data recorder capable of recording weights up to 100 kg through a metal ring. Each lever movement had weight recorded at three locations through its path: at the start of the pull, during the middle of the pull, and just prior to completion of the pull. The three point measurement gave insight into the variations the signaller was dealing with during the lever operation – the taking up of slack, the quality of the channels and any changes in direction of the connections.

There were a number of limitations to the measurement of weight/force carried out in these early stages of the study with the crude device. The method was only able to give discrete point reading of weight rather than dynamically throughout the range of movement. The device itself changed the way in which the signaller pulled the lever, not a problem if the weights were likely to be consistent but in our case the multiple links between lever and moved object meant that the pulling action and effective weight would differ each time (overcoming inertia and taking up any slack, which varied). Also it soon became clear that a capability to measure weights of over 100 kg was required. Nonetheless the early recordings provided an excellent first indication of lever weights, and therefore of the potential for risk of poor performance in lever operation and especially of harm to the signaller. It helped to justify the extension of the study to many boxes using design and development of a more sophisticated measurement device.

The new measurement device was developed with the aim of assessing a much greater range of weights of the lever pull/push while allowing the signaller to operate the lever as close to normally as possible and not intruding on the signaller's work. The device also had to be flexible enough to fit the large variety of lever handle shapes and sizes, be portable to take to a large number of boxes across the whole country, and be robust. The new instrument consists of a sleeve device with a strain gauge inside which fits over the range of lever handles, attached to a copy handle which lies in

Fig. 4. Main lever weight measurement device.

the same plane a few centimetres away; this allows the copy handle which is pulled/pushed to be of normal lever diameter and by displacing it somewhat two people could pull the handle if the risk was thought to be a large one (Figs. 4 and 5). Weight is measured through a shear strain measurement device placed at the bottom of the handle (use of shear force means that turning moments do not have to be considered so that it does not matter where the copy handle is grasped). A tiltmeter is also incorporated so that measured weights can be calibrated against the angle of the lever and so video stills of the posture at any point in the pull/push can be matched to the weight measured. The data acquisition software loaded onto an attached laptop computer captured all the various measures on a time base.

The procedure in each box visited was as follows. The test equipment was set up, comprising the artificial lever handle with the strain gauge inside it, the data logger attached by wire to the lever to collect the data, and a laptop computer connected to the logger to download and view the data. The signallers were then asked to pull the lever and return (push) it three times, using the attached lever as the handle. The measuring device recorded the weight moved (in kilograms) via the handle throughout the entire pull and push back. Three repeated measures were taken to allow the signaller to adjust to pulling the lever, since the "extra" handle was slightly further forward than the normal lever, and because of the natural variation in weight on each pull and push due to changes in the pulley or rodding systems and any slack or lack of which builds up.

Fig. 5. Lever weight measurement in action.

3.2. *Protocol for small in-depth sample phase*

As outlined above, the measurement programme has taken place in two phases, each with a specific purpose. The first phase was an in-depth collection of data at a small number of signal boxes. The purpose of this phase was to establish the nature of the problem and collect a wide range of data to help develop criterion levels and to establish a basis for a first assessment and management programme. The boxes that were selected were those where there had been previous reports of lever pulling problems or because other ergonomics audit work was to be carried out there. The total number of boxes in this sample was six.

In each box, on arrival at site the ergonomics team observed the signaller operating the levers and asked the signaller and manager a series of questions about the levers, their maintenance, difficulties and so on. Direct measurements were taken of clearance between the levers and between the levers and a front wall, and any box aspects that may hinder the signaller in pulling the levers – floor type, footboards, frame type, etc. – were noted. Drawings were made of the levers and the links to the points/signals, the distances from levers to operated object noted, and photographs and videos (of lever operation) taken. Signallers were asked for their subjective impression of lever weights and movement difficulty, rating each lever which was to be measured subsequently as "light", "medium" or "heavy". Details of the signallers' posture(s) and strategy when pulling the lever (see later), as well as personal details such as age, weight and sex, were taken. Then the direct measurement of weights took place, as described above.

All data were collected on one standard form. Table 1 provides a summary of the information collected for two example levers/boxes.

3.3. *Protocol for large pre-screened sample phase*

Once it had been established from the first set of measurements that a potential problem existed for the company the measurement

Table 1
Two examples of data collected for each lever.

Signal box	A	B
Date of visit	13.2.09	21.5.09
Lever number	30	7
Frame type	S + F Rocker	GWVT6
Lever type	Distant Signal	Points
Distance to signal/points (m)	1115	58
Space in front of lever (cm)	Clear	140
Signaller height (cm)	176	179
Signaller build	Heavy	Light
Strategy of pull	Swing	Drag
Signaller rating of lever weight	Heavy	Medium
Pull reading 1 (kg)	79	42
Pull reading 2 (kg)	86	48
Pull reading 3 (kg)	103	37
Push reading 1 (kg)	28	12
Push reading 2 (kg)	15	17
Push reading 3 (kg)	16	19
Pull mean (kg)	89	42
Push mean (kg)	20	16
Pull maximum (kg)	103	48
Push maximum (kg)	28	19

programme was extended across the Network Rail system of mechanical signal boxes in the most efficient manner possible. This meant implementing a stage of pre-screening and prior risk assessment. Managers were contacted and asked to identify the degree of difficulty that their staff were experiencing with the different levers in their box(es) and then to inform the Ergonomics Team of any which were reported as being especially heavy or especially difficult to operate. The process of pre-screening allowed concentration of resources on the most critical cases, rather than establishing the full range of weights across all levers in all boxes. Any estimates of the mean and standard deviation of lever pull and push weights for the large sample therefore would be meaningless due to the initially skewed sample, but this was not the main priority in a practical exercise aimed at achieving a feasible risk assessment programme.

The data collection procedure for the large pre-screened sample was simpler than for the in-depth sample. The ergonomist(s) visiting the box confirmed with the relevant manager and signallers which were the levers reported as "heavy" and they were asked to explain why this was. Then the relevant signaller or signallers were asked to operate the relevant levers for the ergonomist to examine the posture adopted and the pulling strategy used. Then the weight of the pre-identified lever(s) was measured. Subsequently the ergonomists would discuss with the relevant staff the risk posed by the lever or levers and ways in which this risk might be mitigated in advance of the system being redesigned or replaced; the topics covered were the pulling strategy used, potential risk factors (such as slippery or raised floors, restricted movement space), precautions to be taken and the value of a full maintenance programme.

Levers in over 160 additional boxes have been assessed in this main programme.

3.4. Injury and lost work time statistics

Data on lost time accidents due to lever operation were obtained from the company's safety management system and from human resources sickness records. These sources were analysed to highlight injuries and sickness which could reasonably be interpreted as related to the operation of mechanical lever frames.

3.5. Biomechanical modelling

Following the initial site visits and data collection, typical postures and weights moved were modelled in the biomechanical human modelling tool JACK. The main focus of the modelling was to establish the possible changes in type and level of potential injury risk with different weights of lever pull and for different operating strategies and postures. We recognise that it would be very difficult to model in detail all the postures and pulling strategies used in practice, for instance where these involved one foot being in the air for a while, and also any sudden changes in the pulling motion during the range of motion which may increase risk though jerk forces; therefore we treated all modelling work and analyses with caution.

Video recordings of the pulling strategies and postures (see below) at a variety of boxes were used to build signaller lever pulling models representing a range of postures (see Fig. 6). The first phase analysis was carried out for the swing method of lever pulling. Using this method, the signaller uses (usually) two hands to pull the lever forward, starting with arms bent and the body close in to the lever. During the motion, the feet remain stationary and act as a pivot. As the end of the arc is reached, the arms straighten and the back remains straight. For phase 1 of the modelling the signaller was modelled as a 50th%ile male – 175.49 cm tall, weighing 77.69 kg – shown in Fig. 7 at nine stages throughout the duration of the lever pull. Weights of 50, 80, 100, 185 kg were modelled to represent three different possible alert and action levels as regards a risk management programme and the maximum weight found in field measurement (180 kg) was modelled in addition. Subsequently, for phase 2, 5th, 50th and 95th percentile populations (male and female) were modelled in a variety of postures although only for the stages of the pull and push where peak compression forces were expected, with lever weights of 50, 80 and 100 kg (i.e. not including 180 kg as this had already been shown clearly to be beyond any acceptable limit).

4. Results

4.1. Lever weights for in-depth sample

The first small in-depth sample was of six signal boxes where all lever weights were measured, postures and pulling strategies observed and signaller subjective ratings of weight/difficulty were taken for all the levers. Key results for this are summarised in Table 2. The mean lever weight was 51.33 kg. However, in order to decide how to take the subsequent larger sample later the mean weight was not the issue but the range was, and particularly for the weights at the upper end of the distribution. Pull weights across the boxes varied from 8 kg to 155 kg, an enormous range reflecting the wide variety in lever system design and condition. The space in front of the levers within which the signaller must operate also varied widely, with some evidence that greater difficulty was experienced for similar lever weights when space was more limited.

Signallers were questioned about their perception of the weights of each lever they normally operated in a box, reporting

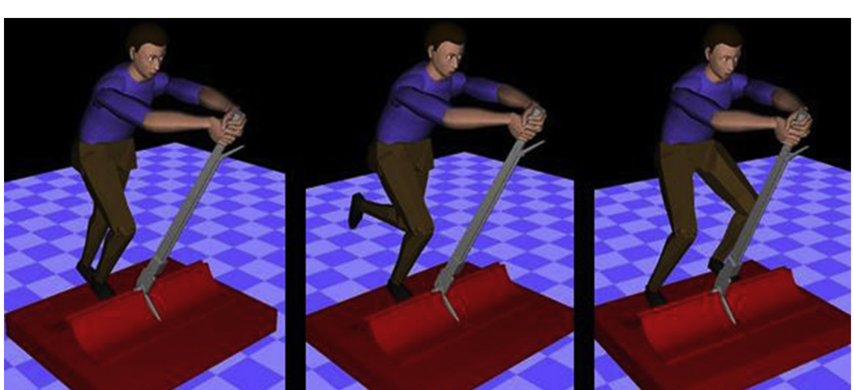

Fig. 6. Range of postures modelled in JACK.

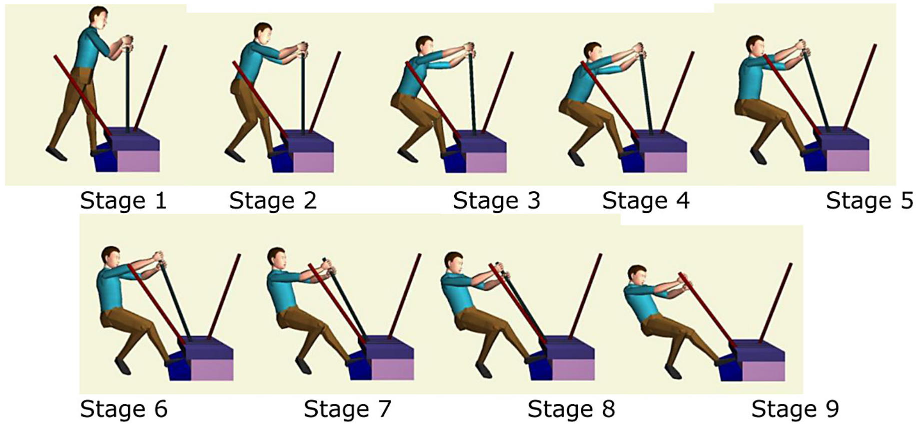

Fig. 7. Stages of lever pulling used in biomechanical modelling analysis.

Table 2
In-depth first sample – measured lever pull weights (in kg) sorted in columns by signaller estimate of weight.

Signal box	Rated high by signaller pre-measurement	Rated medium by signaller pre-measurement	Rated low by signaller pre-measurement
C	55, 85	30	8, 14, 16, 19, 22
D	50, 98	28, 45	10, 14, 19, 22, 22
E	78, 92, 110, 120, 140 155	92	–
F	98	26, 31, 34, 34, 40, 44, 65	14
G	135	86	–
H	69, 74	14, 27, 31, 44, 45, 50, 58, 59	18, 22, 23, 24, 24, 32, 58
Mean	97.07 kg	46.47 kg	21.16 kg

these as heavy, medium and light without having sight of the actual measured weights. This was done for all signallers in the six boxes of the initial sample and for a number of others until we began to be confident with the findings; a total of 126 levers and signaller ratings were taken in this way. The perceptions of the signallers are quite indicative of the actual weights. By and large a signaller started to rate a lever as heavy at a measured weight of about 50 kg, with very few rated as light or medium above 60 kg (see Fig. 8). We suspected some influence of signaller stature and body size on the pulling strategies used (see below) and their ratings of lever weights. But there is no strong statistical evidence.

4.2. Lever weights for large pre-screened sample

The large pre-screened (risk assessed) sample covered over 160 signal boxes. One or more levers, according to the pre-screening reports, were measured and operating behaviour and posture recorded for the usual signaller on that lever. The sample was

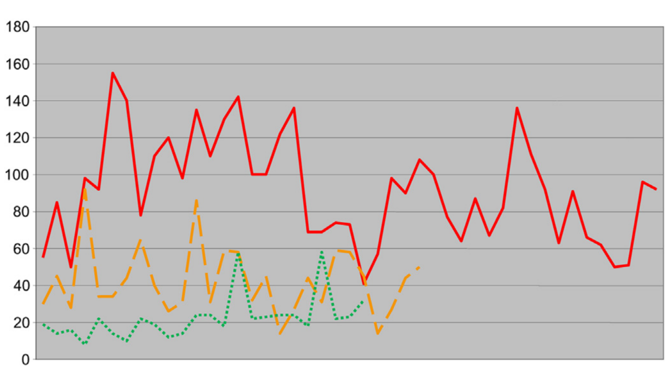

Fig. 8. Graph of actual measured lever weight against signaller ratings of weight/difficulty: Key: Red solid line: Signaller rated heavy; Amber dashed line: signaller rated medium; Green dotted line: signaller rated light. [For interpretation of color referred in this figure legend, the reader is referred to web version of the article.]

almost entirely male (94% with 6% female), reflecting the workforce at that time. Average stature was 174.5 cm; 35% were judged to be of heavy build, 40% medium build and 25% light build.

Table 3 illustrates the type of results obtained, showing these for a random set of seven levers of the larger, pre-screened (risk assessed) sample. Data collected include three readings each for pull and push weights, their averages, strategy/posture adopted, basic data on the signaller and the distance to the operated element (signal or points). It must be remembered that measurements were only taken for those levers previously rated by the signallers and their managers as heavy or difficult, and so the general level of measured weights is much higher than for the first in-depth sample. These levers almost all have a mean, or at least a maximum, pull weight of 50 kg, confirming crudely the ability of signallers or their managers to judge the weight or difficulty of a lever and giving some credibility to thoughts of 50–55 kg as an initial alert (if not action) criterion level. Of around a thousand "heavy" levers across the 160 boxes only 30 were measured as being below 55 kg pulling weight for either maximum or mean (and only 13 below 50 kg for maximum). In total over 70 levers were measured at over 100 kg maximum pulling weight. The distribution of weight ranges for those levers measured as over 55 kg weight is summarised in Table 4. Details for the 10 heaviest pull and 10 heaviest push lever weights are in Table 5.

Push weights were found to be less than the pull weights, from marginally so to over 30% less. This is due to the mechanical construction of the links from the levers to the signals/points, and the mechanism of back weights employed.

In addition to the above, the frequency of operation was discussed with the manager and signaller; this varied from once a day or less to operation for every train, which could be 8 or 10 or more times per hour.

4.3. Operating strategies

When assessing risk of musculoskeletal disorders in manual handling the postures adopted are as critical as the weights being

Table 3
Examples of data collected per lever in large pre-screened sample.

Box	Lever	Type	Pull					Push				
			1	2	3	Mean	Max	1	2	3	Mean	Max
BGY	2	Signal	79	86	103	89	103	28	14	16	20	28
BGY	4	Signal	44	33	43	40	44	11	11	11	11	11
BGY	25	Points	118	111	112	114	118	69	72	76	72	76
BTW	47	Signal	85	73	65	74	85	28	35	36	33	36
BTW	52	Signal	94	72	93	86	94	22	20	21	21	22
BTW	2	Signal	85	67	72	75	85	15	18	15	16	18
APP	12	Points	91	127	125	114	127	20	40	30	30	46

moved. Moreover, since one of the aims of the research was to suggest training in improved lever pulling it was important to study and compare the different strategies and postures actually adopted by signallers, the variation in which had been pointed up by pilot work. Therefore in each box the investigators observed the lever pulling technique of the signallers who were on duty and recorded this. For the first boxes visited records were made via digital photography and video taping, but later when the team were more confident in distinguishing strategies and postures the recording was by eye with handwritten notes.

The postures adopted and the lever pulling strategies varied considerably. Observation and questioning led us to understand that the methods used depended on a combination of individual signaller preferences (perhaps influenced by the body size and weight of the individual), the space available to pull the lever in the signal box, design of the frame, the weight and position of the lever itself, and any previous injury or bad experience. The strategies have been described by us in three basic types: swing, drag and shuffle.

a) **Swing** method of lever operation starts with the signaller gripping the lever either with one or two hands, dependant on whether their approach is hindered by other levers already pulled over in the frame. Once the lever is released from the trigger catch in the frame there is a short pause in motion but grip is maintained on the lever. The arms are bent with the trunk of the body drawn in close to the lever and the body is then thrown backwards with the feet maintaining their position, and the back kept straight. The arms straighten until the weight of the lever is balanced against the force and weight of the body's backward movement (Fig. 9). This movement appears to be dependant on the signaller's knowledge of the lever frame's idiosyncrasies.
b) **Shuffle** method is similar to the swing method with a slight variation in the concluding part of the movement. The body mass cannot be accommodated under the lever's arc and therefore the signaller has to shift while the lever movement is coming to its end. This requires the legs to carry out a shuffling movement backwards in order to prevent collision between body and lever.
c) **Drag** method starts as with swing and shuffle, but most often there is no pause or trigger release in its early stages. The signaller literally drags the lever through its arc of movement with the whole body moving back in synchronisation. The signaller's trunk gradually bends forward as the movement of the lever brings it towards them, ending with the signaller bent over the lever (Fig. 10).

Table 4
Distribution of those lever weights measured as over 55 kg across 160 signal boxes.

Weight range	Number of levers in range	Percentage
55–79 kg	57	30%
80–99 kg	53	27%
100–119 kg	40	21%
120–139 kg	20	10%
140–159 kg	12	6%
160–179 kg	9	5%
≥180 kg	2	1%

Across the whole sample, the swing method was used by 58%, drag by 25%, shuffle by 9%, and for 8% the posture/method was indeterminate.

When levers had to be returned to their normal position in the frame, signallers used one common method, which was mainly a reversal of the drag method. The pushing posture has to accommodate the arc of the lever, bending to get under the angle in order to gain the initial momentum.

Interviews carried out with the majority of signallers observed revealed the reported factors influencing their postures and pull/push strategies to be: weights to be operated; smoothness/roughness of the operation (caused by poor design or maintenance of the connecting wires or rods; tightness of wire adjustment; box design; space (or lack of it) in front of the levers; frame design (whether raised or not); general physical environment; age of signaller; build of signaller; general health of signaller; any previous injuries; previous experience of wire breaks (meaning a sudden change in force/weight); and any training received in operation (rare). Particular attention was paid to recording instances of where "jerk" forces could be required, where extra force is required to overcome initial inertia or if there is a snag or jam in the middle of the pulling or pushing action (HSE, 2004, clause 95).

Table 5
Maximum lever weights for pull and push.

Signal box	Lever no.	Lever type	Weight in kg
Top 10 lever max pull weights			
CCG	12	Signal	184
CAM	21	Points	181
CGT	11	Points	179
SLL	22	Points	178
EGG	3	Points	176
GRI	20	Points	173
STH	12	Points	167
ABB	60	Points	166
ANC	30	Signal	166
LON	14	Signal	164
Top 10 lever max push weights			
SLL	22	Points	153
WKG	36	Points	138
SLL	6	Signal	132
INV	23	Points	125
FRR	6	Points	111
PLF	46	Points	111
NJU	15	Points	111
BLK	38	Points	108
WTJ	57	Points	107
WHT	20	Points	103

Fig. 9. Swing method of lever operation.

4.4. Modelling

For the purposes of the first biomechanics modelling of the lever pulling task, using JACK, it was assumed that the signaller pulled against a weight directly opposing the motion, and that this force acted through the signaller's palms. It was also assumed that each arm took half the total load (certainly an incorrect assumption in many cases but a decent approximation), and that gravity = 10 N/kg. Therefore for the weights modelled in the first phase, of 50, 80, 100 and 185 kg, the loads assessed were 500, 800, 1000 and 1850 N, crudely allocated as 250, 400, 500 and 925 N per arm. The potential lower back compression is given in Newtons within the JACK software; nominal risk of lower back injury for most healthy workers occurs at below 3400 N (the National Institute for Occupational Safety and Health (NIOSH) Back Compression Action Limit); above 3400 N is defined as an increased risk of lower back injury for some workers and it is recommended that these jobs be modified to reduce lower back compression forces; and above 6400 there is an increased risk of lower back injury for most workers and it is recommended that the job should be re-engineered immediately to reduce the risk of lower back injury. The simulation results, giving the lower back compression in Newtons, are shown in Table 6 and in Fig. 11.

It can be seen that the model predicts that the signaller is at a nominal risk of injury whilst operating levers of both up to 50 kg

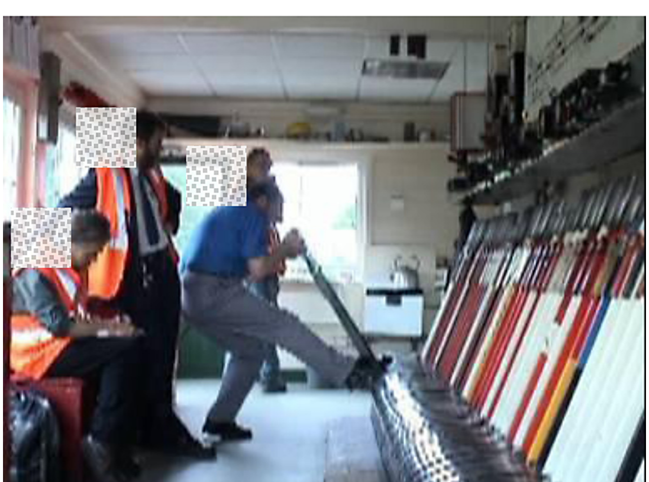

Fig. 10. Drag method of lever operation.

Table 6
Simulation results for lower back compression forces (in Newtons) and 50th%ile operator model.

Stage of action (see Fig. 7)	Weight of pull in kg			
	50	80	100	185
1	1267	2159	2757	5291
2	1334	2250	2802	5192
3	1239	1943	2237	4276
4	1374	2357	2295	5954
5	1574	2367	3024	5757
6	1861	3009	3760	6988
7	1608	2329	2829	5129
8	1688	2457	2989	5178
9	2104	3112	3788	6220

and also of 50–80 kg weight. Increased risk of injury is identified at 100 kg during stages 6 and 9 of the pull. Interpolating from Fig. 10 shows that the weight at which the level of risk increases is approximately 95 kg. The simulation of the heaviest recorded pull weight shows that the signaller is at increased risk of lower back injury throughout the pull, and this risk increases in severity at stage 6 for pulls over 175 kg. Fig. 11 can also be used to predict that the risk for most stages of the pull will not increase to a caution or alert level until a pull of around 118 kg is recorded.

In analysis of the data collected in the second modelling phase, using a wider range of body sizes and of pulling postures/strategies, the compression force was found to be 6900 N for a 5th%ile operator (male plus female) with 100 kg lever weight (Fig. 12). This is above the risk level for most workers of 6400 N. All compression forces for 80 kg and 100 kg weights and 50th and 95th%ile users were in the range 4100 to 6300 N, above the risk limit defined as relevant for some workers.

4.5. Injury and lost time statistics

Injury and incident data were examined for 95 of the sites where measurements were carried out, to identify incidents leading to sickness absence which mention "lever" or "lever operation" or similar. A total of 272 incidents were recorded over a six month period (about 6 incidents per box per year). Most of the reports record circumstances as "whilst pulling (or pushing) lever(s)" and the injury site is generally back, neck, shoulders or abdomen, although the data made no distinction between chronic and acute injury. The total absence was 1628 days giving an average of six days sickness absence per incident, with a mode of 7 days and a range of 1–39 days. One estimate is that each day of absence incurs a cost equivalent to three days wages to the company, meaning a

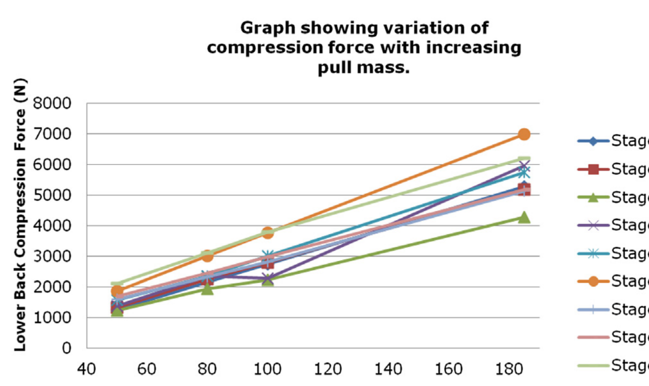

Fig. 11. Compression forces in the body predicted by JACK plotted against lever weight for each stage of the pulling action, 50th%ile operator.

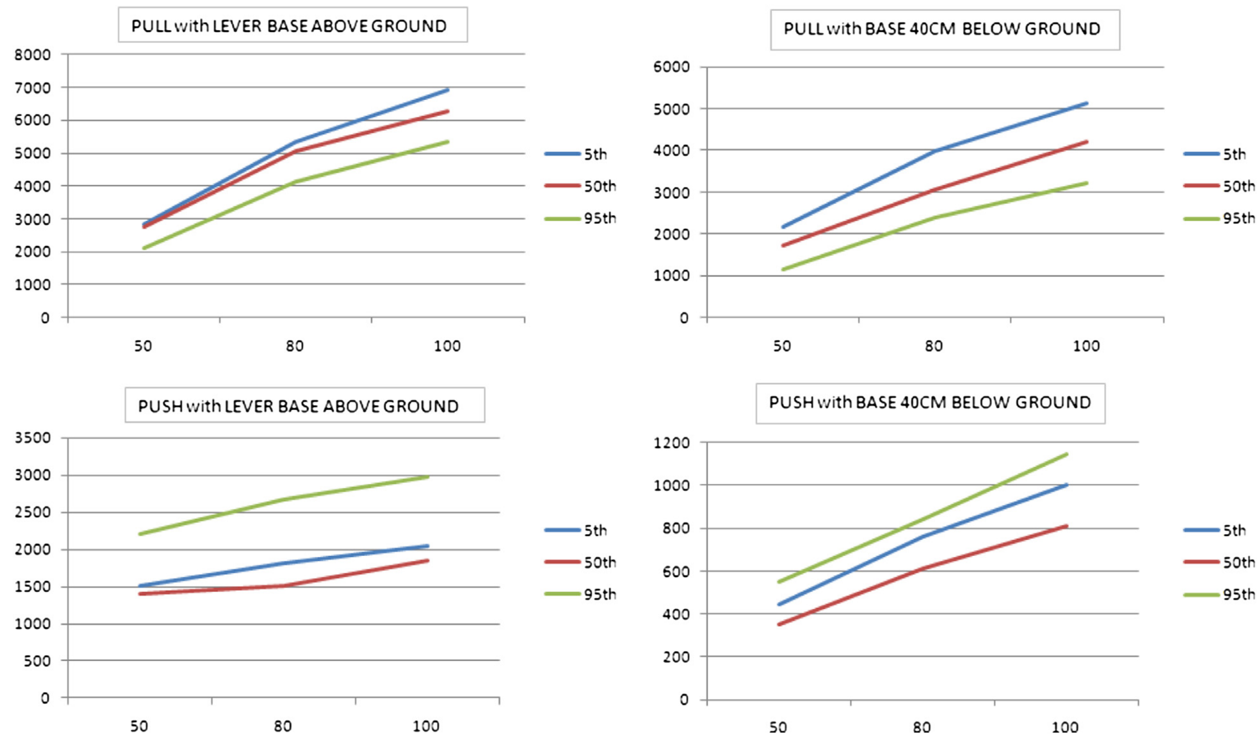

Fig. 12. JACK modelling results for 5th, 5th and 95th%ile operators and for different lever frame configurations.

total annual cost of several millions of pounds in addition to the distress, inconvenience and worse caused to injured signallers.

5. Discussion

5.1. Summary of study purpose and approach

The key aspects and distinguishing factors of the study reported here are:

- It was carried out in response to a real need by a major business, with the focus and methods changing in response to the earlier data collected (almost as a kind of action research approach)
- It involved measurement, in the field, of weights being moved in as close to real conditions as possible (that is with minimum interference from the measurement device or process)
- The task focus – vertical lever pulling and pushing from a standing position – has not been studied in any published work previously and there are no directly applicable design or risk level guidelines.
- The host company wanted to inform a risk management programme in the most efficient way possible, and so a pre-screening or first risk assessment approach was taken in a larger (second) phase of lever operation observation and lever weight measurement.

5.2. Acceptable loads/weights

The main component of the research reported in this paper was the measurement, throughout the arc of movement, of the weights of pulling and pushing points and signals levers in mechanical signal boxes. This was done to begin with for all levers in a small sample of signal boxes, in order to establish the likely range of weights and the association of measured weights with signallers' ratings of difficulties. Subsequently weights of only those levers pre-screened and assessed as "heavy/difficult" were measured as part of a programme to cover many mechanical signal boxes on the network. This was done because the need is to identify sources and levels of risk in the most efficient way possible and not to provide a full record and distribution of the weights of all levers. This was a practical piece of applied research and not a pure scientific (experimental) study. Thus the first small sample provided an idea of the total range of lever weights to be expected and, importantly, the association between actual weight and signaller rating of weight and difficulty, whilst the second larger sample was a pragmatic effort to identify where a risk management programme should be targeted. The key questions for the measurement programme were: at what lever weight should caution be applied, at what weight should the risks be managed as part of a planned programme, and at what weight should prioritised action be taken?

Although none of the published manual handling guidance from around the world appears to be directly applicable to lever pulling we made some interpretations of what was available. We also held discussions with ergonomists working with railways in other countries, for instance Australia. This led to us proposing a first potential alert level as 55 Kg weight. Interestingly, from the data in Table 2, it appears to be at about 50–55 kg that signallers tended to rate lever pull weight as heavy or difficult, giving some credibility and face validity to the 55 kg first alert limit. This alert limit could be used to identify levers and boxes where initiatives such as training and awareness campaigns should be implemented. However, because of the varying frequency of lever use, from many times an hour to a few times a day, we looked for a higher action limit at which to require actions which would include redesign and renewals. Examination of the lever weight data across the second pre-screened sample and the two phases of biomechanical computer modelling established 100 kg as an acceptable action level for a feasible risk management programme.

Interestingly, although it might seem from much of the literature on manual handling risks that frequency of operation would present a risk factor (with the more frequent the handling activity the greater the risk), in fact the opposite can be true for rail mechanical signalling. From the interviews and general discussions in the many boxes visited, it seems that very occasional use of a lever may present a greater risk because of the signaller's lack of familiarity with the best suited posture, the weight that needs to be taken up, and the "feel" of the pull including any possibilities of sudden changes in resistance and hence weight. Also, the less frequently used levers may be more prone to deterioration and hence non-smooth running through to the signal or points, or in worst case scenarios to sudden breakage.

5.3. Strategies and postures and modelling work

Pilot observations had made clear that different signallers adopt different strategies to pull and push levers and take up different postures during the action. Many factors may influence the signaller-lever frame interface, and therefore influence the strategies for pulling and pushing adopted by signallers; these strategies will rarely if ever have come about through formal transfer of good practice or training. The method adopted by an individual could be influenced by body size, frame and box design, including the space available and custom and practice in each box.

Three basic strategies have been identified which are adopted by signallers to move levers - drag, swing and shuffle. The movements and postures involved in these do not relate easily to standard manual handling tasks. Whilst "drag" could be related loosely to "pulling" as defined within various manual handling regulations, "swing" is a matter of using the body weight to counter the force needed to move the lever. Swing appears to be the style adopted by smaller (both weight and height) persons. Shuffle is an adaptation of swing, but because the arc of the lever is such that the body cannot be accommodated within the last part of the movement of the lever (due to box layout), they have to extricate the lower half of the body from under the moving lever. This movement appears to be associated with persons of a larger girth. Anecdotal evidence also is that signallers may change strategy after an injury or a sudden event with the potential to cause injury, such as a wire breaking suddenly.

The first biomechanical modelling exercise in JACK provided predictions of risk at somewhat higher weights than might be assumed from the evidence from the signallers' own estimates of weight or from interpretation of such manual handling guidance limits as exist. For the swing strategy the greatest risk to the signaller is identified as being at stage 6 of the swing (see Figs. 6 and 10). At this stage, risk would be increased at a pull of about 95 kg. This seems to indicate an action target weight limit of about 100 kg. The first modelling results were treated with caution. First, only the swing method was modelled and it is possible that other levels of risk would be obtained if modelling the shuffle or drag strategies. Second, even for swing the load was arbitrarily allocated 50/50 to the two arms, which is highly unlikely in practice; a different allocation may bring other movement stages into the risk categories, perhaps for 80 kg and even 50 kg weights. Third, the first analysis was based upon an average male but signallers come in both genders and all weights and sizes, with risks likely to be higher at the extremes of stature. The second phase of modelling addressed some of these cautions, modelling with 5th, 50th and 95th%iles, and representing a number of lever frame designs and positions; however, only peak weights were taken from the simulation. This second phase work confirmed that serious risk concerns (compression forces of over 6400 N) were clearly identified for lever weights of over 100 kg, but that concerns for nominal injury risk (over 3400N) were found for weights of 80 kg when smaller signallers and different frame designs were modelled.

5.4. Management programme

This paper has addressed the question of the risks of operating levers in mechanical lever frame rail signal boxes from two perspectives. The first perspective is the measurement (and modelling) involved in understanding what the weights are that are being pulled/pushed, the consequent forces being applied and the risks to the individuals. However, the second and key perspective is the pragmatic one, the company's need to manage potential risk from lever operation. On the basis of the research reported here the company has put in place a risk management plan for signallers working with lever frame boxes. Evaluation work to extend from the first study was written into the company Ergonomics Strategic Plan; interestingly, once the work had started with the drive coming from the Ergonomics Team there has been recognition at the operations levels in the organisation that this was an issue which required a strategic approach. Most importantly, a procedure "Location risk assessment to be followed when a 'heavy pull' is reported by a signaller" was written into the signalling Operations Manual.

The components of the risk management plan and strategy for action are as follows:

1. Continue with the pre-screening plus risk-based measurement programme as reported in this paper. Signallers and managers are required to report any boxes and levers where there have been reports of heavy pulls/pushes or where there have been injuries. These levers are then assessed initially by maintenance as the problem can often be rectified by remedial works. Maintenance staff have been provided with simple portable strain gauges to support them. If the weights cannot be reduced through maintenance then a full assessment is undertaken by members of the Ergonomics Team using the approach and methods described here, which is usually the start of the process for more significant modifications.
2. A simpler, lighter and cheaper measurement device is under development with the intention to send it out to all the mechanical lever boxes over a rolling period for personnel to measure and monitor their own lever weights. This device will not be sophisticated enough to assess the weights being pulled at various points through the pulling and pushing actions but will be used simply to find the maximum weight for any one lever. Any report of a lever weight over the action level set will trigger a more extensive study by either the Ergonomics Team or, in a participatory approach of spreading ergonomics throughout the company (e.g. Wilson, 1994), by operations staff trained by the ergonomists.
3. Because the box conditions and therefore weights and difficulty of lever operations change over time, a local risk assessment programme is being implemented. This involves the local managers in using the simpler measurement devices and checklists and recording sheets developed by the Ergonomics Team for use locally. The managers monitor the opinions and insights of the signallers, if necessary measure the weights involved in lever pulling and pushing and identify any new difficult pulls which emerge over time. The reporting is used to determine whether a more detailed risk assessment by qualified ergonomists is required. This programme helps ensure that the company meets its legal obligations under manual handling regulations, to conduct risk assessments on a regular basis within a basic participatory programme, and to share ergonomics with the stakeholders.

4. Many problems with the heavier levers are due to deterioration of the equipment, channels and linkages, not picked up by preventive maintenance over the years. Ironically, because of the increased use of computer-based signalling, the company's expertise in mechanical signalling maintenance is slowly eroding. Therefore, a guidance note has been produced by the company and sent to all relevant staff on how and where to carry out routine maintenance to ensure that for any one design and layout the weights being pulled and pushed are as low as practically possible.
5. Observations during this study made clear that different signallers use different strategies and adopt different postures to operate the levers. In part these postures are associated with the design of the levers, the space available to pull them and the body size of the signaller, but in part reflect practice adopted by certain signallers and boxes over the years. The most appropriate aspects of these pulling strategies will be synthesised with good practice taken from general manual handling guidelines - such as working symmetrically where possible, working from solid, flat and non-slippery footing, allowing sufficient space, using two hands and arms where possible, and using an appropriate posture. This will form the basis of a guidance note, initially to be issued to signallers at induction and also in safety briefings
6. The guidance note will be further developed into a specialist training programme for all new and existing signallers in lever frame boxes. This may supplement the existing manual handling training given to all new and current signallers.
7. Over and above the maintenance and training parts of the risk management programme, there will be some residual risks where the weights of the levers are sufficiently high, the frequency of operation sufficiently frequent and the circumstances of operation sufficiently difficult that a programme of re-fitting and redesign is required. Examples of such re-fit are straightening rodding runs, renewing points and changing to power operated levers. This has not been cheap to carry out due to the need to carry out works over a long run distances, and figures of over £100,000 per lever have been quoted. Therefore such a renewals programme needs to be implemented with care; the total cost to date is close to £3 million.
8. In order that a feasible renewals programme is initiated which also meets the priority to improve signaller health and safety, the key question remains: At what weight limit should any renewals be implemented. We have seen that signallers start to rate levers as being heavy to pull at about 50 or 55 kg, and the biomechanical modelling showed a nominal risk of injury also at this weight (although this does not necessarily mean that the risk becomes unacceptably serious at this weight). Further modelling showed a definite alert level of risk at 100 kg weight for all types of signaller, postures and frame designs, and weights of 80 kg were approaching an alert level. Therefore the revised Operations Manual defines: a weight of 55–79 kg as a first action level requiring local actions and improvements: a weight of 80–99 kg as a second action level requiring maintenance mitigations and formal further assessment; and a weight of over 100 kg as meaning that the lever should be signed out of use, until the weight can be reduced to a safe level.

6. Conclusions

This paper has reported the development of a programme to manage the risks of injury to rail signallers using large levers in mechanical signalling boxes for the operation of signals and points. The key risk was identified early on as being the weight being moved by pulling or pushing a lever, and therefore the main need was to establish limits to such weights. However, due to the nature of the task, the moved element being fixed at one end, there being a defined arc of movement in one plane and the great variation in frequency of operation, none of the existing manual handling regulations and guidelines seemed directly applicable. For similar reasons, the literature on pushing and pulling (maximal or recommended forces) was of limited value. Therefore an innovative programme of measurement and assessment was set up. Amongst other findings, the lever pulling and pushing postures and strategies used were identified, the ability of signallers to consistently and relatively accurately distinguish light, medium and heavy levers was confirmed, and generally acceptable limits were identified for weights which should initiate alert, initiate action and lead to lever withdrawal from service. Due to the wide sample taken in the field, and the biomechanical modelling which took different genders and body sizes, there is confidence that these limits, and the other risk factors identified and communication, have provided the basis for a sound management programme. Nonetheless, until more evidence is available from the operation of the plan, and also more laboratory research has been completed, the management of injury risk is being approached with caution and the outcomes are under continual review.

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References

Attebrant, M., Winkel, J., Mathiassen, S.E., Kjellberg, A., 1997. Shoulder-arm muscle load and performance during control operation in forestry machines. Applied Ergonomics 28, 85–97.
Ayoub, M.M., McDaniel, J.W., 1974. Effects of operator stance on pushing and pulling tasks. AIIE Transcations 6, 185–195.
Boyer, J., Lin, J.-H., Chang, C.-C., 2013. Description and analysis of hand forces in medicine cart pushing tasks. Applied Ergonomics 44, 48–57.
Galer, I., 1989. Applied Ergonomics Handbook, second ed. Butterworths.
Gallagher, S., Heberger, J.R., 2012. Examining the interaction of force and repetition on musculoskeletal disorder risk: A systematic literature review. Human Factors. http://dx.doi.org/10.1177/0018720812449648 (in press).
Health and Safety Executive, 2004. Manual Handling Operations Regulations 1992 (as amended). Guidance on Regulations L23, Third Edition. HMSO, London.
Hoozemans, M.J.M., van der Beek, A.J., Fringsdresen, M.H.W., van Dijk, F.J.H., van der Woude, L.H.V., 1998. Pushing and pulling in relation to musculoskeletal disorders: A review of risk factors. Ergonomics 41, 757–781.
Kroemer and Grandjean, 2000. Fitting the Task to the Human. A Text book of Occupational Ergonomics, Fifth Edition. Taylor and Francis.
Kroemer, K., Kroemer, H., Kroemer-Elbert, K., 2001. Ergonomics: How to Design for Ease and Efficiency. Prentice-Hall, NJ.
Lee, T.-H., 2007. Pushing strengths under restricted space. Human Factors and Ergonomics in Manufacturing 17, 95–102.
Lee, K.S., Chaffin, D.B., Herrin, G.D., Waikar, A.M., 1991. Effect of handle height on lower-back loading in cart pushing and pulling. Applied Ergonomics 22, 117–123.
Lin, J.-H., McGorry, R.W., Chang, C.-C., 2012. Effects of handle orientation and between-handle distance on bi-manual isometric push strength. Applied Ergonomics 43, 664–670.
Page, G.B., McMahan, P.B., Brown, R.T., 1990. The development of ergonomic guidelines for railroad hand switch operations. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, October, 748–751.
Resnick, M.L., Chaffin, D.B., 1995. An ergonomics evaluation of handle height and load in maximal and submaximal cart pushing. Applied Ergonomics 26, 173–178.
Rohmert, W., 1966. Maximum force exerted by men in the zone of movement of the arms and legs. Forschungsberichte des Landes Nordrhein-Westfalen Research Report No. 1616. Westdeutscher Verlag Koeln-Opladen. (English translation: Library Translation No. 1939, Royal Aircraft Establishment, Farnborough).
Rohmert, W., Jenik, P., 1971. Isometric muscular strength in women. In: Shephard, R.J. (Ed.), Frontiers of Fitness. C. Thomas, Springfield, IL, pp. 79–97.

Seo, N.J., Armstrong, T.J., Young, J.G., 2010. Effects of handle orientation, gloves, handle friction and elbow posture on maximum horizontal pull and push forces. Ergonomics 53, 92–101.

Wilson, J.R., 1994. Devolving ergonomics: The key to ergonomics management programmes. Ergonomics 37, 579–594.

Wilson, J.R., Norris, B.J., Clarke, T., Mills, A. (Eds.), 2005. Rail Human Factors: Supporting the Integrated Railway. Ashgate, London.

Wilson, J.R., Norris, B.J., Clarke, T., Mills, A., 2007. People and Rail Systems: Human Factors at the Heart of the Railway. Ashgate Publishing, Abingdon, UK.

Wilson, J.R., Mills, A., Clarke, T., Rajan, J., Dadashi, N., 2012. Rail Human Factors around the World: Impacts on and of people for Successful Rail Operations. Taylor and Francis, London.

Wojtczak, H., 2005. Railwaywomen: Exploitation, Betrayal and Triumph in the Workplace. Hastings Press.